



RESEARCH DEPARTMENT



REPORT

**SOLID STATE SENSORS:
the use of a single dimension 512
element array for film scanning**

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THE USE OF A SINGLE DIMENSION 512 ELEMENT ARRAY FOR FILM SCANNING
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Summary

Following some early experiments with a 72 element self-scanned linear array of photo-diodes, a 512 element array was obtained. This has been used to scan continuously moving film since this provides a convenient means of assessing the potential of single dimension solid state image pick up devices. The method of application and the resulting performance are discussed.

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1. Introduction

A single dimension 512 element self-scanned array of photo-diodes was purchased so that the usefulness of such a device for television image sensing could be assessed. The work was undertaken to gain experience in the use of solid state sensors particularly with regard to the possible future use of more complex area arrays in television cameras. If such devices could be used in cameras a considerable power and weight saving would result, together with improved geometry and longer life.

At the time the array was purchased it was the most complex device readily available and the only one capable of operating fast enough to provide standard television pictures with reasonable resolution. In view of the high cost of the array earlier work has been undertaken with a 72 element array. As a result of the earlier work we were reasonably certain that the larger array could be used to produce television images from film even if the pictures had, because of experimental limitations, to be on a non standard scanning system.

The 512 element array has been used to provide the line scan of images on continuously moving film, field scan being provided by the motion of the film.¹ The work has progressed through several stages of improvement up to a point where we can produce reasonable quality monochrome television pictures which can be recorded on a standard quadruplex video tape recorder or reproduced directly on a normal television monitor.

2. The array

2.1. Construction

The array is the Reticon self-scanned 512 element linear sensor array type RL512 and is shown in Fig. 1. This is an integrated circuit which contains a single row of 512 light sensitive diodes; the image is focused onto the diodes through a ground and polished quartz window which forms the top of the dual-in-line package.

Along each side of the row of diodes, and integrated onto the same silicon chip, is a 256 bit shift register. Each element of the shift registers drives an f.e.t. switch which can connect one of the diodes to an output bus bar. Alternate diodes are connected to one bus bar by f.e.t. switches driven by the register on one side of the array and those in between are connected to a second bus bar by the other register.

2.2. Scanning

To scan the array a logic '1' is put into each shift register and the clock pulses cause these '1's' to propagate

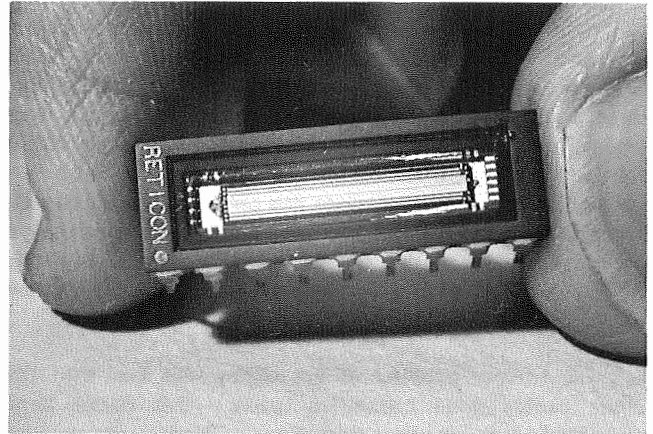


Fig. 1 - Reticon 512 element single dimension array

through the registers. As the logic '1' reaches each position in a register the corresponding f.e.t. switch connects the diode to the bus bar. By clocking the two registers out of phase the signals from successive diodes appear alternately in time on the two bus bars. The signals from the two bus bars are brought out to separate pins on the package and can either be separately amplified or added together and fed to a single amplifier.

2.3. Signal output

The method of signal output is known as re-charge sampling. The output bus bars are held at a constant bias voltage. As each diode is connected to the bus bar by its f.e.t. switch it becomes reverse biased and its self capacitance is charged to the bias voltage on the bus bar. During the time between scans this charge is depleted by carriers generated by the incident light. On the next scan the capacitance is recharged to the bus bar bias voltage and the integral of the current which flows from the bus bar is equal to the charge which has to be replenished. This charge is therefore equal to the integrated effect of the incident light between scans. Broadly speaking the instantaneous current flowing in the bus bar represents the integral of the light falling on the array between successive scans. The array therefore has a linear light in/signal out transfer characteristic. For the use described in this report the integration time is the television line period (64 μ s).

3. Clock pulse breakthrough

There is an inherent tendency for clock pulse spikes from the clock inputs to the array to appear on the signal output due to capacitive coupling within the chip. Under saturation conditions the signal current replenishes a charge of about 2 pC on the capacitance of each light-sensitive silicon diode. The original voltage on the diode is about 5V so that since

$$Q = CV$$

The capacitance of each diode, $C = \frac{2 \times 10^{-12}}{5} = 0.4 \text{ pF}$

On the other hand the clock signals switch between +5v and -12v and it follows that a capacitance of only 0.12 pF between a clock line and the output line will produce a peak signal current due to differentiated clock edges which is as large as the signal current. It was previously found that the position of the wiring of clock pulses external to the chip is critical since this can easily have a capacitance to the output signal line such that the clock spikes are much greater than the signal current pulses. For this reason a very careful layout must be used to keep the clock and signal paths well separated.

A further problem is caused by the fact that the clock pulses drive capacitive loads; this causes large currents to flow on clock transitions. These currents cause a voltage drop in the inductance and/or resistance of the earth lead. Care has therefore to be taken to see that these voltages do not add to the signal output.

Clock spikes can, however, be cancelled since for every positive spike there will be an equal area negative spike, whereas the signal current appears in only one polarity. Apparently, then, it is a simple matter to integrate the output current over one clock period to cancel the effects of the clock spikes. However, it is necessary to amplify the signal before this integration can be made and the amplifier must be capable of handling the large clock spikes.

Moreover, at high sampling rates (10 MHz) it is not practical to integrate the signal output over the whole of one clock period (100 ns) as is sometimes suggested in the literature. The result of each integration must be sampled and the integrator must then be reset before being used again. The latter requires almost the same time interval as does the integration. Thus at least two integrator systems (each integrating alternate clock pulse periods) would be required and it is unlikely that they could be matched in terms of gain to a sufficient long-term accuracy to prevent the output signal being amplitude modulated at half the clock frequency.

A much easier approach is to filter the output signal with a passive filter which has a cut off frequency at about half the clock pulse frequency (i.e. allowing the maximum possible signal frequency to pass), and near infinite attenuation before the clock pulse frequency is reached. Since clock spikes can (at first sight) only have components at the clock frequency or its harmonics, they should be removed. Practical results of this approach are discussed in Section 6.4.

4. Scanning for a television system

4.1. Line scan

The width of the part of the image on the film which

will be reproduced depends upon the physical length of the array and the magnification of the lens used to image the film onto the array. The width occupied by this image on a television monitor may, however, be varied by changing the rate at which information is clocked out of the array.

In order that the output from the 512 elements of the array should fit the active line time of the television system a clock rate of 10 MHz was used. This is also the maximum specified frequency of operation for the array. The clock was phased locked to 640 times the television line frequency and since this is exactly 10 MHz the active line time for the 512 elements is $51.2 \mu\text{s}$. This is just less than the television active line time of $52.0 \mu\text{s}$.

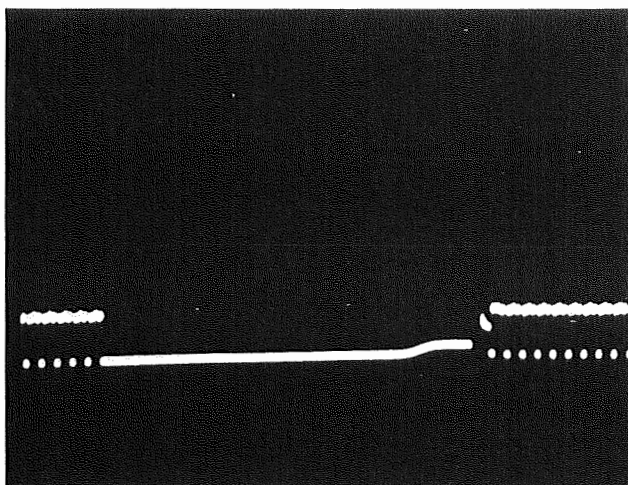
4.2. Television system blanking

A start pulse is required to initiate the scan of each television line. This start pulse is used to produce the logic '1s' which propagate through the scanning shift registers and select which photo-diode is connected to one of the output bus bars. If no start pulses are produced, the array is not scanned and the output will almost be equal to the dark current or black level. Thus during the interval between reading the last diode in the array and the next start pulse the output voltage will be at black level. The generation of a black level signal is therefore automatic, being caused solely by the absence of scanning.

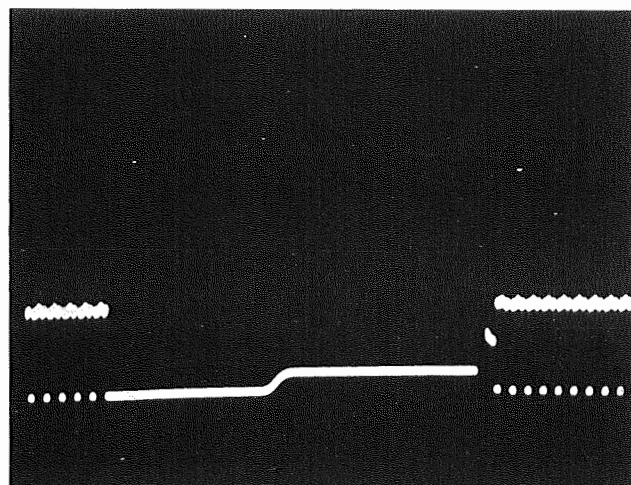
The start pulse is produced by a monostable multivibrator which is either triggered directly by the trailing edge of mixed blanking or from the leading edge of line drive via an adjustable delay. If the start pulse is triggered directly from mixed blanking the array will not be scanned during the field interval. It is however, necessary to inhibit any attempt to scan a half line at the beginning of the active field. (If a scan were started halfway through a line the image for this line would be incorrectly positioned. Also at the start of the first full line the array would still be scanning; a second scanning pulse would enter each register in the array and the attempt to obtain information from two parts of the array at once would produce unpredictable results.)

If the scanning process is stopped during the field interval the array will integrate the light falling on it for the whole of the field blanking interval. Since this amounts to 25 times the normal integration time it is very likely that at least a part of the array will saturate. This saturation in the field interval means that the first line of the next field will produce a saturation white level. This can prove a convenient method of measuring the array saturation level and thus of avoiding the possibility of overload in normal use. It should be possible to scan this 'white line' just before the end of the field interval so that it is subsequently removed by system blanking.

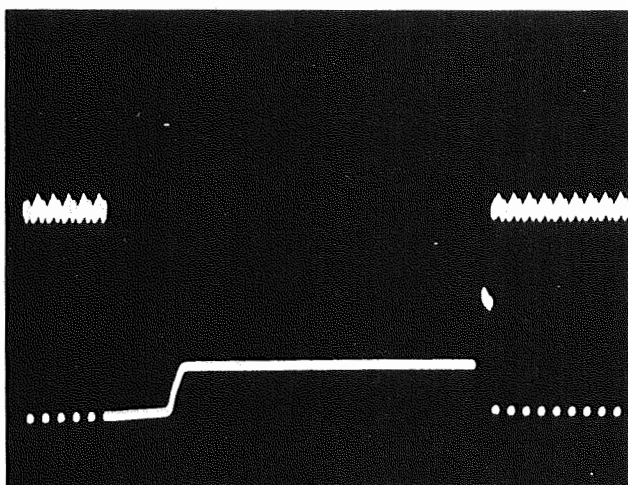
There is, however, one serious disadvantage in allowing saturation to occur in the field interval. It has been found that, at the point during the field interval at which the integrated light level becomes sufficient to saturate the array, there is a step rise in the black level. As mentioned above, when the array is not scanned, the output is virtually



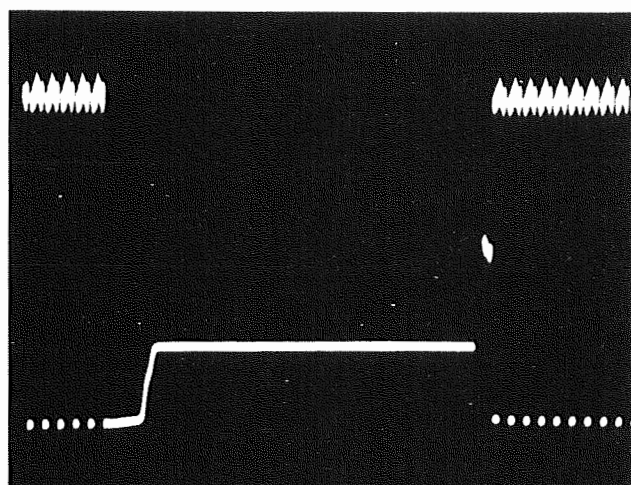
(a)



(b)



(c)



(d)

Fig. 2 - Showing the step rise in black level which occurs when the array saturates; (a), (b), (c) and (d) show how increasing levels of illumination cause saturation, and hence the step, to occur earlier in the field interval

equivalent to black level, or the dark current since no photo-diodes are connected to the output. When saturation occurs, however, the charge on the diodes becomes zero and it appears that some of the junctions in the device cease to be reverse biased and there is a breakthrough to the output.

The step rise in black level is relatively sharp (see Fig. 2) and creates a considerable problem for any clamps in the signal processing system which follows.

It has therefore been found preferable to scan the array throughout the field interval and to subsequently blank the signal output to provide the television system field blanking requirements.

4.3. Field scan

The field scan for a normal television display is at a rate of 50 fields per second and each film frame should be

scanned twice to produce a complete interlaced television picture. The simplest way to produce the required 50 fields per second rate of field scan is to transport the film past the array so that one complete frame passes the array in 1/50th second. This means that the action is at double speed; furthermore, the interlaced field is not produced by a second look at the same frame of film, but from the next frame. This method with the action at double speed and odd and even fields obtained from alternate frames of film, is the one used for the present tests. The double speed action does not present a problem for experimental work; if a normal speed simulation should be required it could be produced by step printing the film so that each original frame appeared twice.

4.3.1. Picture height

With this form of continuous motion scanning the magnification of the imaging system has no effect on the picture height. The film image height which is reproduced

on the television display is a fixed proportion of the film frame pitch, this proportion being the ratio of the number of active television lines in a field to the total number of lines in the field. For this application the scanned height is 92% of the film frame pitch. This is identical to the figure given in the British Standard Specification for the television transmission of 16 mm film.²

4.3.2. Sequential to interlaced conversion

In a practical system the film would be transported past the array at 25 frames per second to produce a 625 line 25 field/sec non interlaced picture. The 575 active lines would then be rearranged by electronic storage to emerge in the order that they would have if interlaced scanning had been used. The total storage capacity required for this is 288 television lines (one television field). Methods for sequential to interlaced scan conversion are described elsewhere.³

Once such a conversion system is used a small amount of additional storage could be added to allow for the compression or expansion of the scanned portion of the film frame height, if required, and to enable the electronic removal of picture unsteadiness such as might be caused by a low quality film transport mechanism.

4.3.3. Still frame

When the field scan depends entirely upon the film movement as it does here there is no possibility of a still frame display. However if a field of storage is being used for sequential to interlaced conversion it should be possible to freeze alternate lines of the last frame which has been scanned at normal speed. With the provision of instant stop this last frame at normal speed would adequately represent the image at the stopping point. It would however be very difficult to update the frozen frame while inching the film.

5. Mechanical arrangement

5.1. Film transport

5.1.1. General

The passage of film frames past the array must be locked in speed and phase to the television system. If the speed is slightly wrong the scanned picture will frame roll, and for the picture to be correctly framed the rack bar must be imaged onto the array during the field blanking interval. Such a system of phase locked film transport is already in common use on twin lens flying-spot telecine machines. To avoid unnecessary mechanical work, therefore, the self-scanned array imaging system was attached to the Research Department twin lens 16 mm flying-spot telecine machine. The additional components are located in the top left hand corner of the cubicle as shown in Fig. 3. The only use which the solid state imaging system makes of the existing telecine is for the feed and take up spools and the constant speed phase locked film drive.

additional components for
solid state film scanning

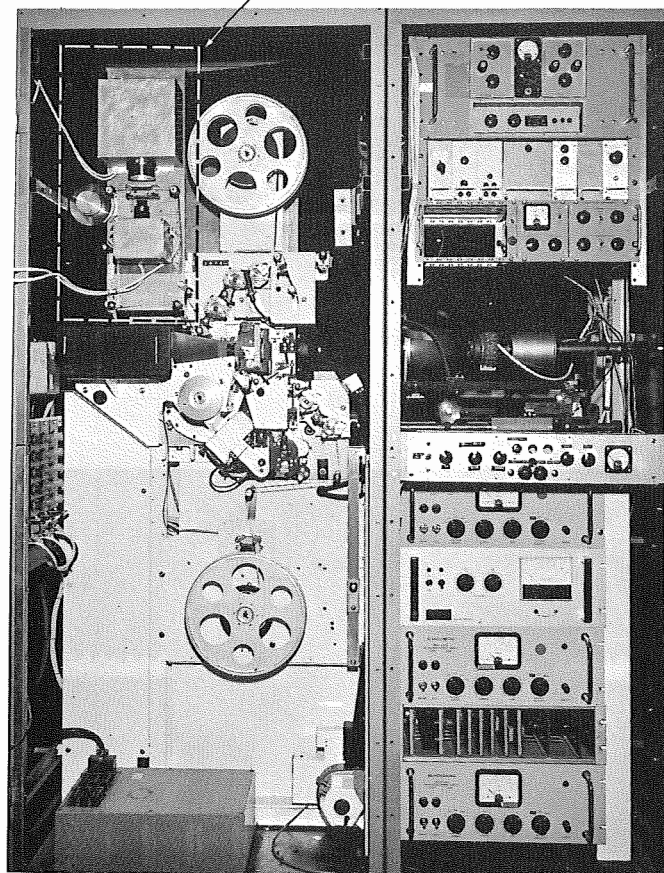


Fig. 3 - Research Department twin lens 16 mm flying spot telecine machine showing the location of the additional components for solid state film scanning

The film lacing path is shown in Fig. 4. It can be seen that the distance from the last driven sprocket to the new optical gate is, unavoidably, rather large, as is the distance from the gate to the next driven sprocket. These large distances give rise to picture unsteadiness due to the varying stiffness of the film, tension rollers in the film path, and variation in the pitch of the sprocket holes. Unsteadiness was also caused by the last driven sprocket before the new optical gate which tended to catch in the sprocketholes at the point of disengagement. This latter effect and virtually all the short term image unsteadiness were removed by the addition of a flywheel capstan adjacent to the gate. The only remaining unsteadiness is a relatively long term picture bounce.

5.1.2. Frame rate

As discussed in the section on field scan, the experimental system required a film frame rate of 50 frames per second. A twin lens 16 mm mechanism is designed to run only at 25 frames/sec and it would be impossible to double

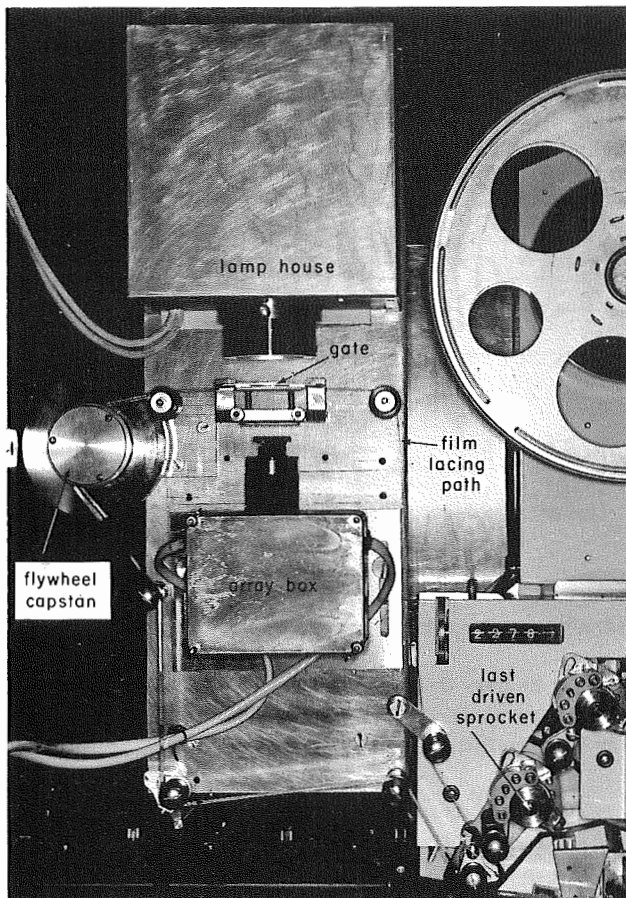


Fig. 4 - Solid state telecine arrangement showing the film lacing path, gate, lamphouse and array box

this speed. It is however a simple matter to substitute a film which has a frame to frame pitch equal to half the 16 mm frame pitch and will therefore run at 50 frames/sec. One such film is standard 8 mm. Standard 8 mm film has twice as many sprocket holes but the individual sprockets are the same size as for 16 mm film. Another useful feature is that standard 8 mm film is printed onto 16 mm film stock (which has perforations at half the 16 mm pitch on both edges) and then slit down the middle to produce two 8 mm prints. For the present tests an 8 mm reduction print was specially made and the slitting operation was not carried out. It was then possible to run this film in the 16 mm mechanism with the sprocket teeth engaging in alternate sprocket holes along one edge of the film. Fig. 5 shows a sample of unslit standard 8 mm film alongside normal 16 mm film.

5.2. The optical system

5.2.1. Lamp house

The lamp house contains a 150 w quartz iodine lamp without a rear reflecting mirror. Light from the lamp passes via a heat absorbing glass into a condenser lens assembly. The condenser lens focuses an image of the lamp filament onto the aperture of the imaging lens. A wide cone of light is formed by the condenser lens and this illuminates a circular area in the plane of the gate which has a diameter of about four frame heights. Since the image is formed

from only a small part in the centre of this illuminated area very uniform illumination is achieved at the expense of considerable light wastage. This wastage was unimportant because there was sufficient illumination of the film for monochrome analysis. If a subsequent conversion to colour analysis were required a mirror could be placed behind the lamp to obtain more light. It should also be possible to redesign the condenser system to waste less light without severely degrading the uniformity of illumination.

5.2.2. Gate

The new optical gate and pressure pad are constructed from spare parts from a commercial 16 mm projector which have been suitably mounted with pressure springs and an edge guide arrangement. The film is biased against the edge guide by the adjustable height guide rollers before and after the gate.

The gate was masked by a slit so that only the area of film imaged onto the array was illuminated; this considerably reduced the effects of flare in the imaging lens.

5.2.3. Imaging lens

The imaging lens is a cheap 28 mm f/4.5 enlarger lens. To image the width of a standard 8 mm film frame onto the array a magnification of about 2.5 is required. A set of spacers were placed between the lens mounting flange

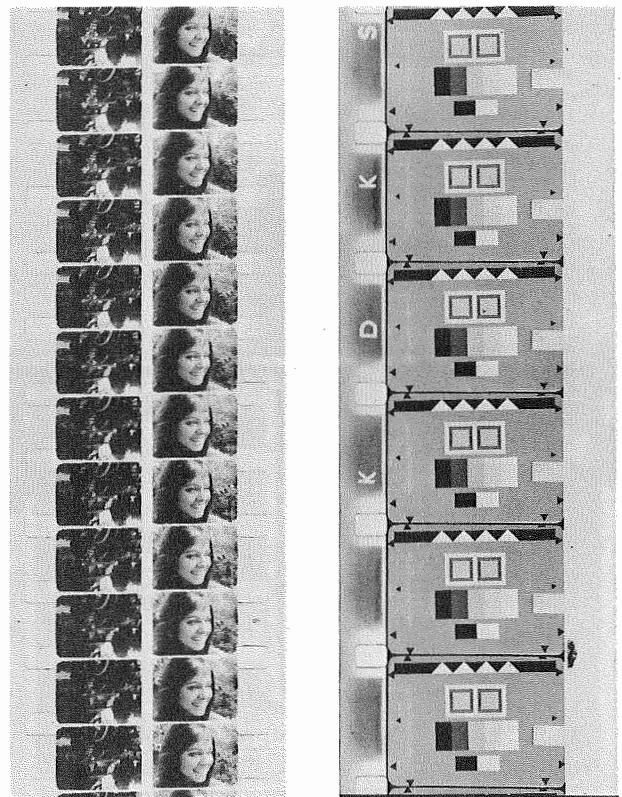


Fig. 5 - Side by side comparison of unslit 8 mm film and normal 16 mm film

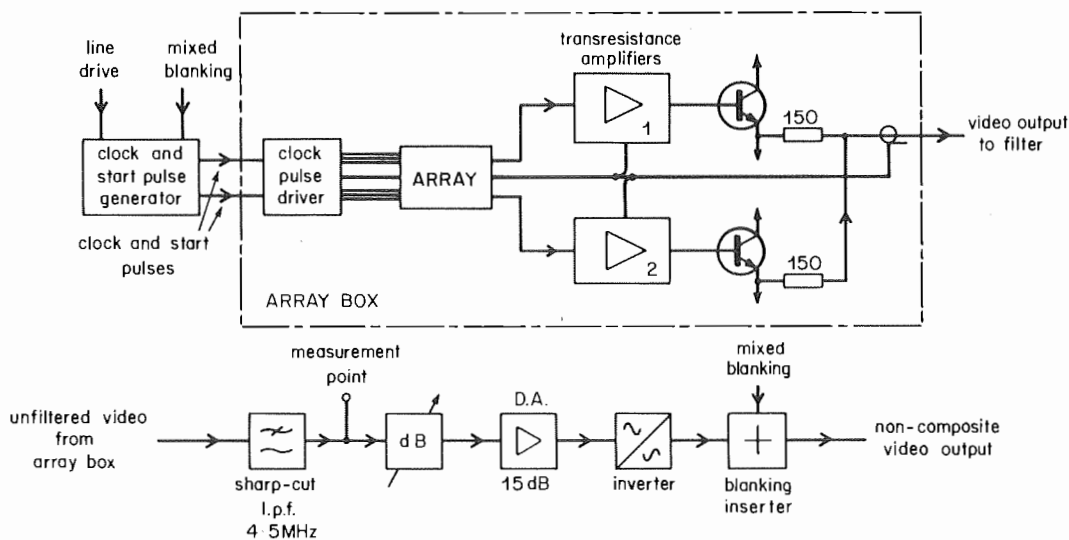


Fig. 6 - Block diagram of electronic circuit arrangement

and the box containing the array to achieve the required lens-to-array distance. The lens body screws into the mounting flange to give small adjustments.

To change the imaging system to suit the 16 mm format some spacers can be removed and the position of the array box relative to the film is adjustable.

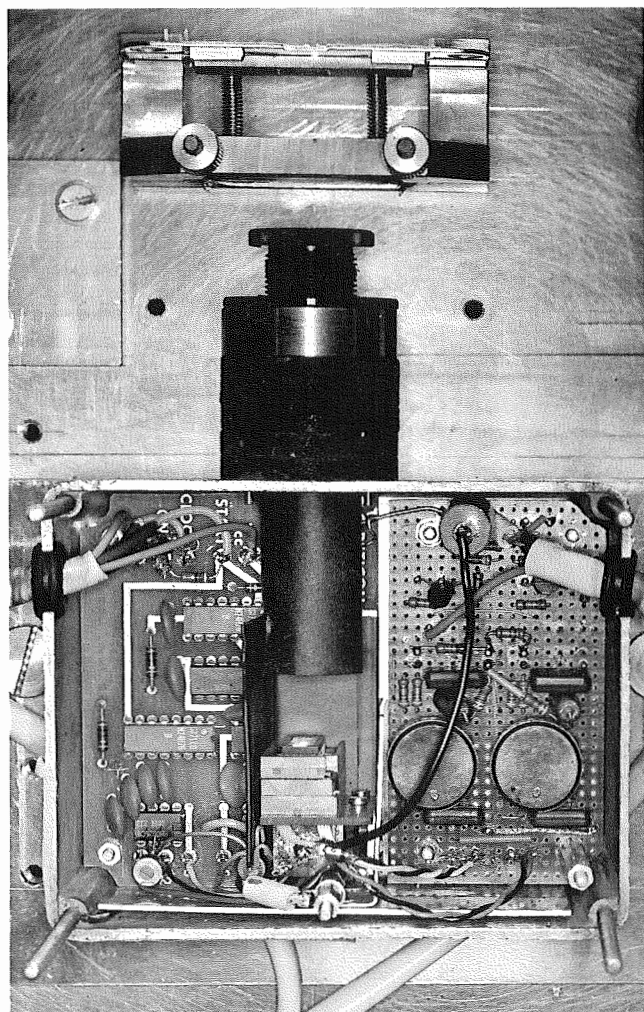


Fig. 7 - Interior of array box

6. Electronic circuit arrangement

A block diagram of the electronic circuit arrangement is shown in Fig. 6. The major components are described below.

6.1. Array box

The array is mounted together with its clock driving circuit and output pre-amplifier in a die cast box as shown in Fig. 7. The array is held by a special socket which is designed to prevent mechanical damage during insertion or removal. The pressure on the socket contacts can be released by operating a lever so that the array can be inserted or removed without applying any force. The sleeving entering the left hand side of the box contains +5v and -12v power supply feeds for the clock driver board together with the clock and start pulses; the pulses being fed via 75Ω coaxial cable. The sleeving on the right contains +12v and -12v power supply feeds to the output pre-amplifier and the video output signal. Separated power supply feeds and cable routings have been used to minimise clock pulse breakthrough onto the video output.

6.2. Clock driver

Each shift register in the array is clocked at half the data output rate i.e. 5 MHz for a 10 MHz data output rate. In addition each register requires a pair of complementary clock waveforms at half the register clock frequency i.e. 2.5 MHz. The clocks for the two registers must be phased so that the two data outputs which each represent alternate diodes are correctly interleaved in time. The resulting requirement is for a four phase clock pulse driver. Each register also requires a suitably timed start pulse.

A clock driver assembly on a printed card was purchased from the manufacturer of the array. This provides the necessary four phase clock and start pulses from a single data rate clock waveform and a single start pulse, each at TTL logic levels.

Since the array presents capacitive loads to the clock driver, large current spikes are generated. The clock driver board was therefore placed in the array box so that the leads to the array could be as short as possible.

6.3. Output pre-amplifier

The manufacturer of the array recommended a circuit for an output pre-amplifier. Each data output is connected to a hybrid operational amplifier connected as a transresistance amplifier.* The voltages from the two amplifiers are fed to emitter followers and then resistively added to form a 75 Ω source. The signal is then taken from the array box via a co-axial lead.

6.4. Removal of clock pulse breakthrough

The video signal from the array box consists of large voltage spikes. These represent the unidirectional current spikes which recharge the diodes together with bidirectional spikes due to clock pulse breakthrough either within the array or between the external wiring. In a slow speed application one would integrate the output signal for one complete clock period, as mentioned in Section 3. The bidirectional spikes due to clock pulse breakthrough would then cancel each other and the integrator output at the end of the cycle would represent the incident light level for the particular diode. This value could be sampled and held until the next data output cycle is completed.

At a data rate of 10 MHz however, a time quantised integration process is not practical and instead a phase corrected sharp cut low pass filter was used. This has a cut off frequency at 4.5 MHz i.e. just below half the data output rate. (The data output is in the form of samples and the maximum available video bandwidth is therefore at half the sampling or data rate i.e. 5 MHz).

At first sight it would appear that with clock pulses at 10 MHz any spikes due to clock pulse breakthrough should have frequency components at 10 MHz and higher harmonics and so should be removed by the filter. Because a four phase clock is used, however, the individual clock frequencies are only 2.5 MHz. Any lack of symmetry of the four waveforms in terms of amplitude, timing, or contribution to total capacitive breakthrough will thus give rise to components at 2.5 and 5.0 and 7.5 MHz. Any 7.5 MHz component would be removed by the filter. At 5.0 MHz the filter has a reasonable attenuation and so the addition of a simple notch filter resulted in its complete removal.

Unfortunately, the 2.5 MHz component is in the middle of the video band and so could not be removed by filtering. It was therefore cancelled by the addition of very

small amplitude clock waveforms to the array output signal. Two potentiometers were connected each between a complementary pair of the clock waveforms. Their slider connections were capacitively coupled to the array output leads by hooking a lead from the slider around the array output lead. By offsetting the potentiometers from their centre positions it was possible to add a small clock waveform of any required phase to the output signal. The two potentiometers effectively provide an in-phase and quadrature control, and their successive adjustment allows almost complete cancellation of any 2.5 MHz component which is present.

The limiting factor is that slightly different cancellation settings are required for signals from either end of the array. It is therefore not possible completely to cancel the component throughout the television line period and a compromise adjustment must be made. The adjustment can however be sufficiently good that the background pattern caused by random variations between individual diodes is greater than that caused by the 2.5 MHz component, (see Section 7).

6.5. Output and display

The output of the filter was further amplified using a conventional amplifier with gain of 15 dB, and inverted to give the normal video polarity. Television System Blanking was then inserted. For the purpose of clamping the input to the blanking inserter the period between line scans was used as the black level reference. The addition of synchronising pulses produced a standard television waveform which could be recorded on a video tape recorder or displayed directly on a monochrome picture monitor.

If the start pulse is derived from mixed blanking so that the array is not scanned during the field interval (as described in Section 4.2) the output signal is already blanked and can be displayed directly on a picture monitor without further blanking. This self-blanking would not be adequate for videotape recording.

7. Performance

7.1. Sensitivity

7.1.1. Incident light level for saturation

It is difficult to make an accurate objective measurement of the incident light level required to saturate the array because of the many variable factors involved, and considerable effort would have been required to take all these factors into account independently. Instead an approximate overall assessment has been made as follows.

The light source was a 150w 24v quartz iodine lamp which was run at 22v to prolong the lamp life. The light from the source was passed through the heat absorbing filter, the condenser lens, and the imaging lens to the array.

The light falling on the array was measured in photopic terms by replacing the array with a small piece of magne-

* i.e. one in which the output voltage is proportional to the input current.

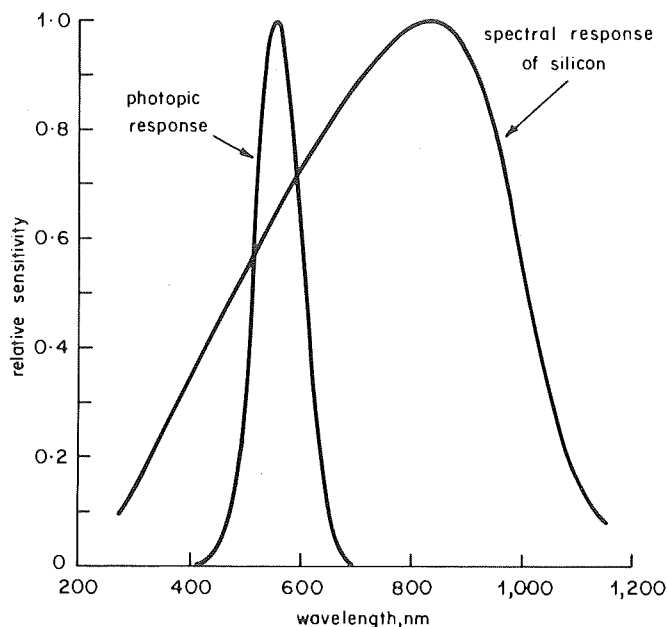


Fig. 8 - Spectral response of silicon and photopic response

sium carbonate block and measuring the brightness with a brightness spot photometer.

A photopic measurement of the light level incident on the array provides only a comparative guide since the array has a spectral response such that it is sensitive to infra red light (Fig. 8) whereas an instrument with a photopic response does not measure light energy in the infra red region. On the other hand, the relative amount of infra red light energy present in the incident illumination is very dependent on the colour temperature of the source and the spectral response of the heat absorbing filter.

The measured incident illumination was 2,450 ft cd. (26.4×10^3 Lux) and this provided an array output signal equal to 90% of the saturation level as shown by Fig. 9. In

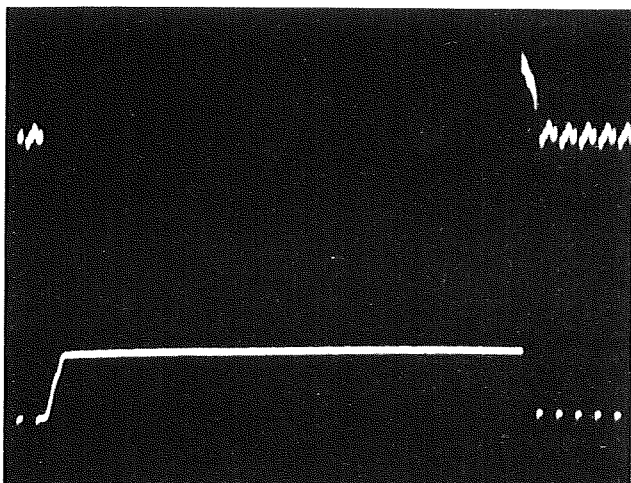


Fig. 9 - Showing the signal level which corresponds to saturation of the array and the relative white signal under normal operating conditions

Fig. 9 the saturation level is indicated by the end of the first white line following the field interval. (The beginning of this line is affected by the step rise in black level which occurs during the field interval when the array saturates as described in Section 4.2; as saturation is removed by reading the first line after the field interval the black level offset is reduced. This is the reason for the tilt on the signal output during the first line.)

The array manufacturer's data states that saturation occurs at an exposure of 6×10^{-2} ft cd. sec (0.645 Lux sec) for a 2870°K tungsten source. Since in our application the exposure time is 64 μ s the illumination for saturation should be 940 ft cd (10.1×10^3 Lux). The large discrepancy between 940 ft cd and 2450 ft cd is easily explained, however, since this photopic measurement of 940 ft cd includes a large implied infra red energy content which in our application is removed by the heat absorbing filter.

7.1.2. Array output current at saturation

The array output was measured in terms of the signal at the output of the low pass filter. Since the parameters of the electronic processing are known the effective signal current from the array can then be deduced.

The array manufacturer's data states that the saturation charge (per element) is 2 pC. Since each output bus bar carries alternate elements the data rate on each bus bar is 5 MHz, which gives a clock period of 200 ns. If a charge of 2 pC is to be replenished in 200 ns the mean current during the clock period will be 10 μ A. (Although the output from the array is in the form of a current spike, the subsequent action of the filter reshapes the spike into a signal which represents the mean value of the spike over one clock period). Each pre-amplifier is such that a current of 10 μ A at the input produces a voltage at the output of 508 mV. After the emitter followers and resistive adding network, the combined signal from the two bus bars becomes 254 mV when terminated in 75 Ω . Allowing for an insertion loss in the 4.5 MHz filter of 0.5 dB the terminated filter output should be 240 mV.

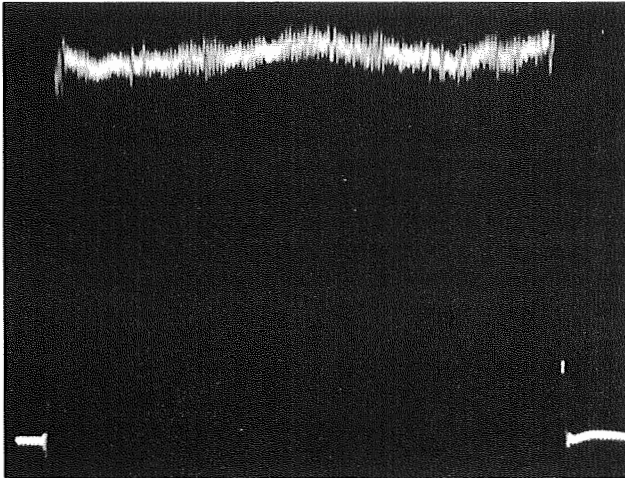
The actual output from the filter at saturation level was 510 mV. In view of the manufacturing tolerances of integrated circuits (say up to 20%) there would appear to be a 2:1 error between the expected and the actual output. The source of the error has not yet been traced.

7.1.3. Noise

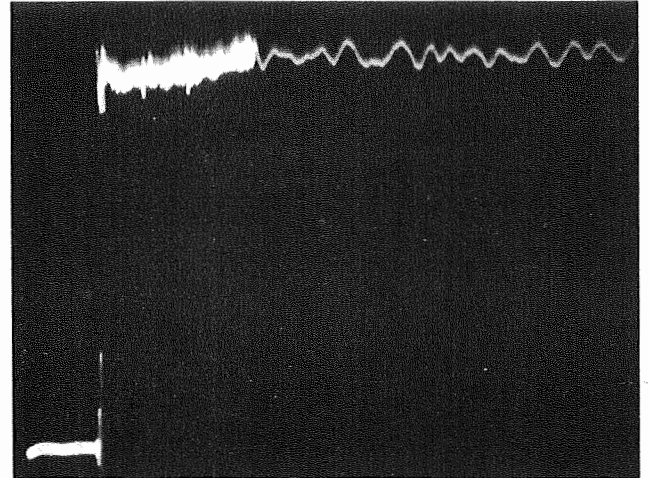
Since the array has two outputs each with a mean current of 10 μ A (or more) it is very unlikely that random noise will ever prove a problem provided the array can be illuminated to a sufficient level. This is in contrast with the upper limit of 300 nA from a conventional plumbicon camera tube.

7.1.4. Element to element variation of sensitivity

Under open gate conditions the white level signal contains variations caused by differences between the sensi-



(a)



(b)

Fig. 10 - Open gate white level waveform showing element to element sensitivity variations together with any shading caused by non-uniformity of illumination

(a) whole television line

(b) part of line expanded to show detail

tivities of individual elements of the array together with any effects caused by non-uniformity of the illumination. Photographs of the waveform at the output of the filter for an open gate conditions appear in Fig. 10. For the purpose of measurement this waveform was also reproduced on an XY plotter using a sampling oscilloscope; the plotted waveform appears in Fig. 11.

The short term amplitude variations have a maximum peak to peak value of $\pm 5.3\%$ of the mean signal amplitude; these variations are entirely due to element to element

sensitivity differences. There is also a longer term variation which may be caused either by variations in the sensitivity of the elements or by non-uniformity of incident illumination. This long term variation increases the overall peak to peak output variation to $\pm 7.67\%$ of the mean signal level.

The array manufacturers specification for sensitivity variations is $\pm 7\%$ and since the uniformity of illumination is quite likely to vary by $\pm 0.7\%$ it is almost certain that the array is within the specified limit.

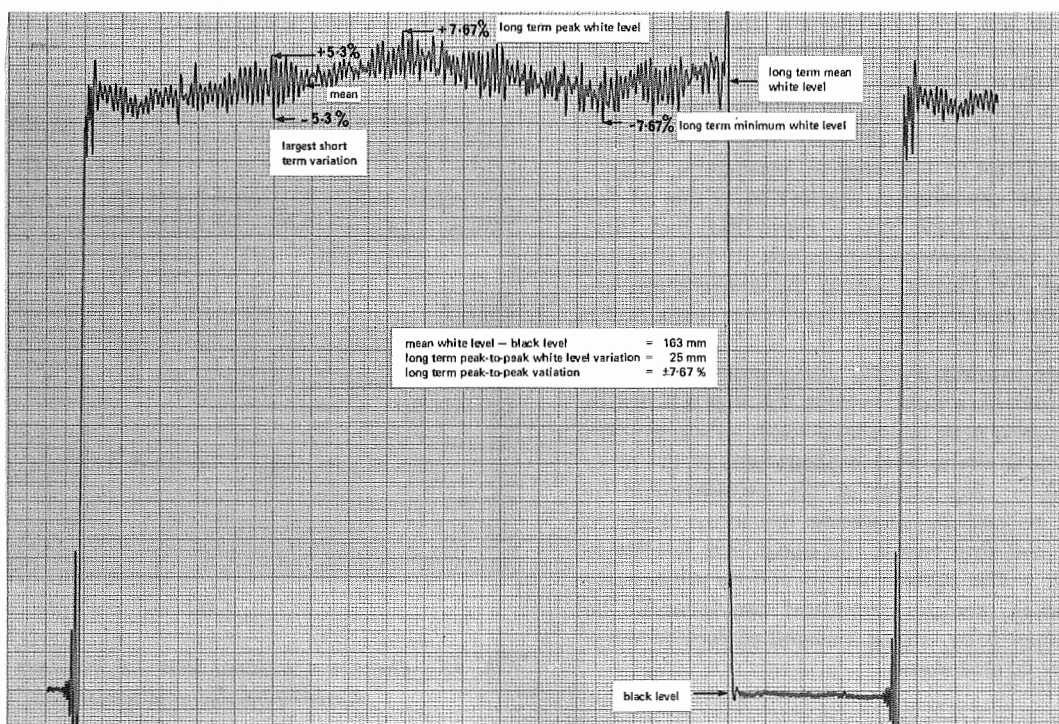


Fig. 11 - XY plot of sensitivity variations obtained using sampling oscilloscope

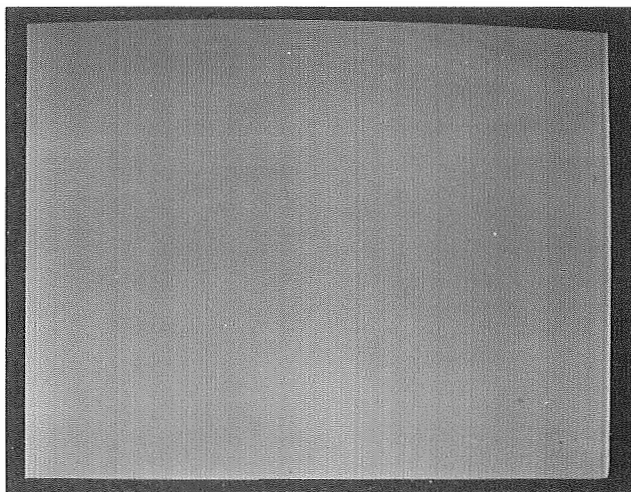


Fig. 12 - Picture taken from picture monitor of striations caused by element to element sensitivity variations

Subjectively, the long term variation is of no importance. On the other hand, the short term variations cause a disturbing striped pattern down the picture as shown in Fig. 12. In any broadcast application this pattern would need to be reduced by passing the array output signal through a modulator driven with a stored correction waveform.

7.2. Dark current and background pattern

7.2.1. General

With no illumination the array produces an output pattern as shown in Figs. 13 and 14. This pattern contains a relatively large 2.5 MHz component together with a smaller random variation due to differences in the dark currents of individual elements. The 2.5 MHz component results from the compromise cancellation for clock pulse breakthrough. Because of different degrees of breakthrough from one part of the array to another the component can either be cancelled at the left hand side of the picture or at the right hand side. Figs. 15(a) and 15(b) show waveforms, which have been obtained via the sampling oscilloscope and XY plotter, where the cancellation has been optimised for the left and right hand sides respectively.

From these waveforms the worst case background pattern magnitude has a peak to peak value of $\pm 1.15\%$ of the normal operating peak white level (with an average film in the gate the peak white level is about 50% of the array saturation level). The effect of the pattern could be reduced by up to half by operating the array closer to saturation level and thus raising the signal level relative to the background. The pattern would still be subjectively disturbing however, and for broadcast use it would be necessary to cancel it by adding a stored correction waveform to the array output signal.

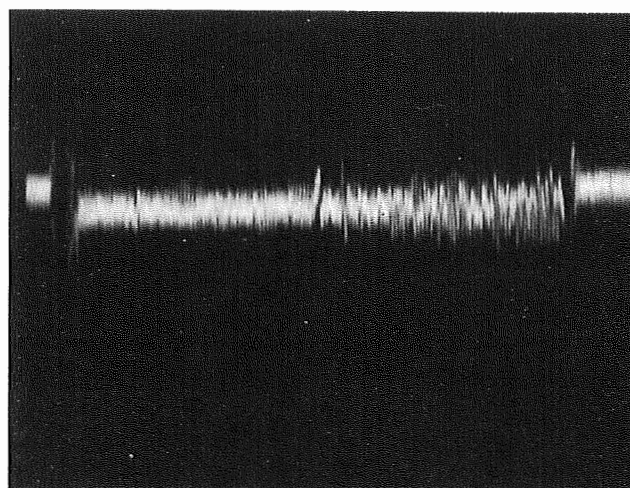
7.2.2. Variation with temperature

The array dark current and hence any background

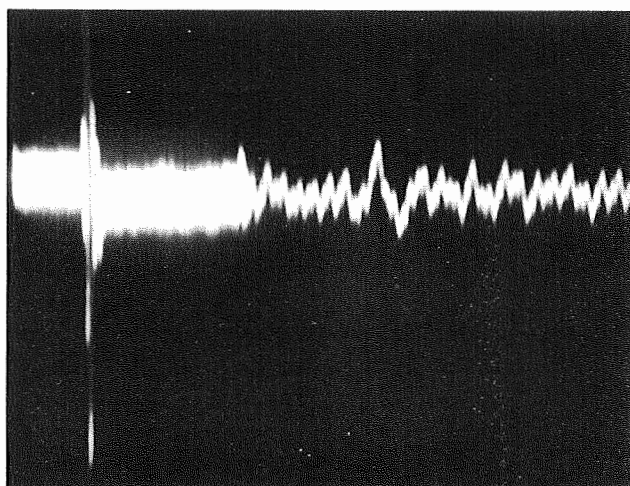
pattern caused by variations of the dark current from element to element may change with temperature. If this should be the case any stored correction for background pattern will only be appropriate for a given temperature. We have not noticed any tendency of the background pattern to change with temperature, but on the other hand any small changes in the overall pattern would be much more obvious if the pattern were first cancelled by a stored correction system. Further work is required to provide stored correction before the effects of temperature variation can be studied.

7.2.3. Contrast ratio

The amount of reappearance of pattern due to a temperature change after a stored correction is applied may provide the main limitation to the minimum light level



(a)



(b)

Fig. 13 - Output waveform with no incident illumination showing background variations

(a) whole television line (b) part of line expanded to show detail
Vertical scale +12 dB (4x) with respect to Fig. 10

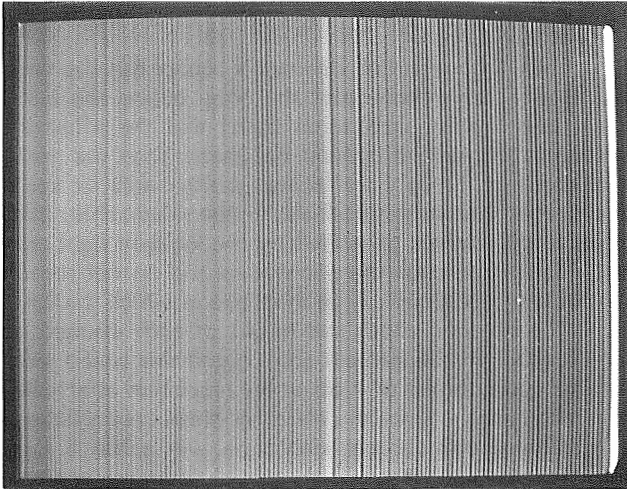


Fig. 14 - Picture taken from picture monitor of background pattern with no illumination amplified by a factor of about ten

which the array can resolve. The contrast ratio which the system can resolve is limited by this ability of the array to resolve low light levels and by flare in the imaging system. Flare in the imaging system is caused by the imaging lens,

by the quartz window in the array package, and by internal reflections within the array package. The amount of flare from the lens was greatly reduced by illuminating only the narrow line of film which is imaged onto the array. (It should be noted that this method of reducing lens flare is a feature which can only be applied to a device which scans in only one direction.) Flare caused by internal reflections within the quartz window and between the array chip and the quartz window is more difficult to overcome. To reduce the reflections between the array and the window all non-light-sensitive areas within the package should be blackened; this would require consultation with the manufacturer. Flare caused by internal reflections in the quartz window could probably be overcome in the vertical direction by tilting the array on an axis along its length so that the incident light strikes the window at an angle. The secondary images due to reflections would then be thrown to one side of the line of sensor elements as shown in Fig. 16. (This also requires a slit gate otherwise secondary images from other parts of the film frame will fall on the light sensitive elements.) Also an extra thick window of neutral density material could be used, as is common practice on flying spot cathode ray tubes.

The ability of the array to resolve low light levels is unlikely to be the factor limiting the eventual contrast ratio of the system. It is estimated that with the background pattern removed the array should resolve light levels equal

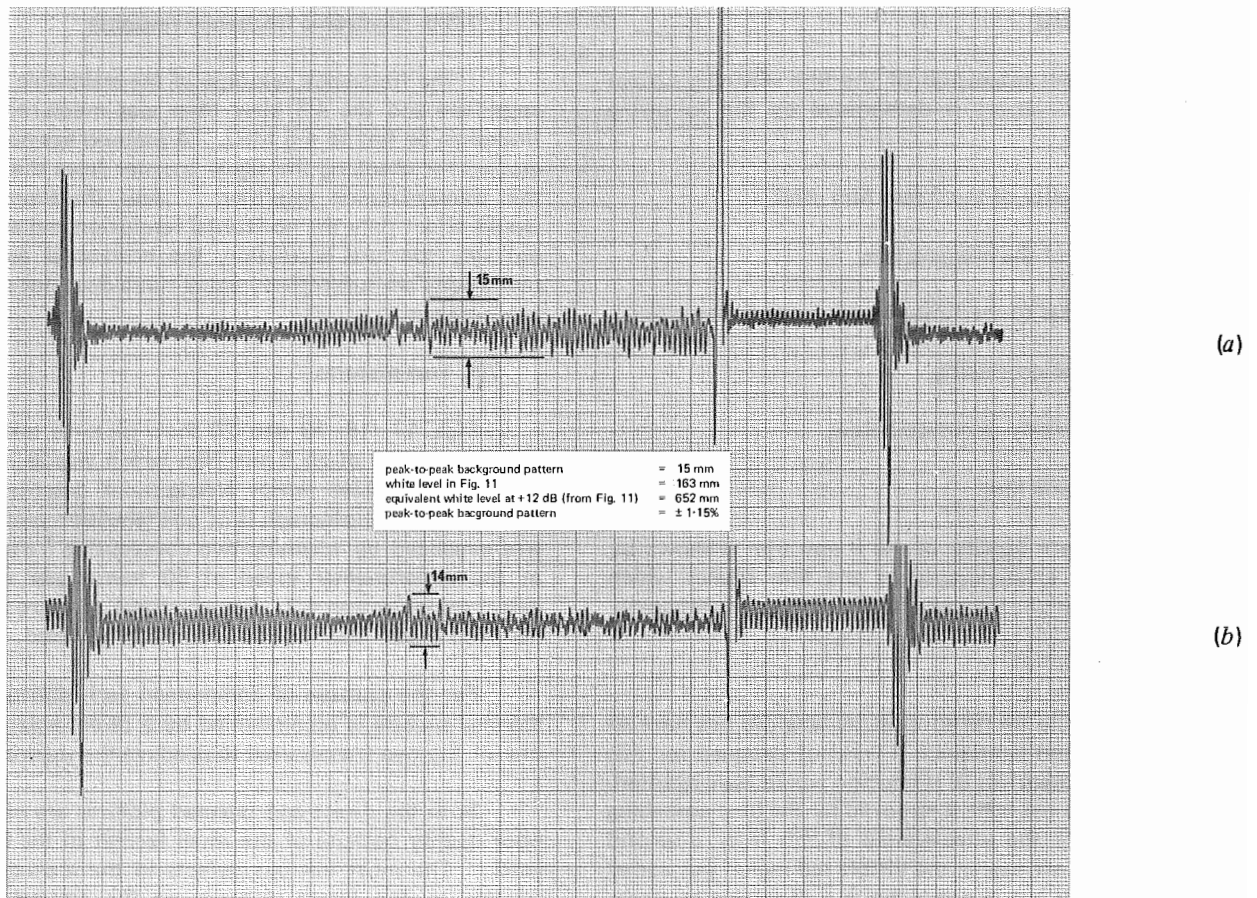


Fig. 15 - XY plot of background variations obtained using sampling oscilloscope
(a) 2.5 MHz component cancelled on left hand side (b) 2.5 MHz component cancelled on right hand side
Vertical scale +12 dB (4x) with respect to Fig. 11

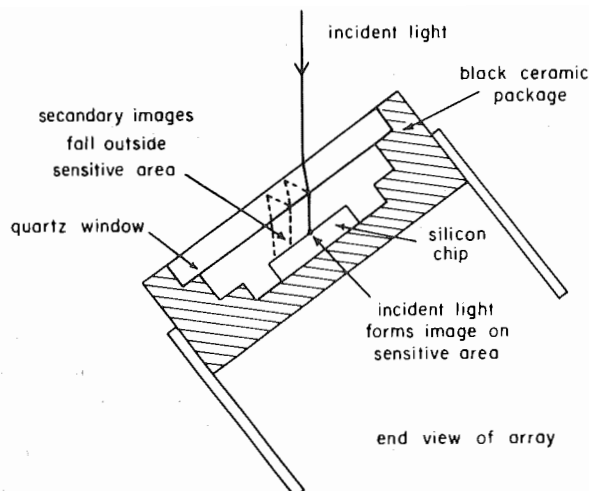


Fig. 16 - Showing how the array may be tilted to remove flare caused by reflections within the quartz window

to one thousandth of the saturation illumination. On the other hand, the present maximum contrast ratio of the array and the imaging system is limited by flare and by the background pattern to about 35 : 1.

7.3. Resolution

7.3.1. General

The overall resolution of the film scanning system described in this report is determined by the following factors.

The picture quality of the 8 mm film used.

The resolution of the imaging lens.

Aperture loss due to the finite element area in the array.

Electronic signal processing.

These are briefly discussed below.

7.3.2. Original film

The picture quality of the 8 mm film is shown by including direct enlargements of the film frames which appear in the test photographs below each test photograph.

7.3.3. Lens

Care had to be taken that the lens did not have to focus any infra red light since it was not designed for this purpose and a serious loss of resolution would have resulted. Most of the infra red light is removed by the heat absorbing filter. To check the effectiveness of this filter, a second filter with a cut off nearer the visible red region was added and since this did not improve the overall resolution it was concluded that the original filter was adequate. Any loss of resolution in the lens will normally affect the horizontal and vertical definition equally.

7.3.4. Aperture loss

Each light sensitive element is square but the film image is moving vertically past the array during the integration time (giving integration blurr) and the effective vertical aperture will, therefore, be greater than the horizontal aperture. Also the effective sensitive area for each diode is larger than its physical area on the silicon chip; this is because the carriers generated by the incident light can travel sideways through the silicon slice and do not necessarily deplete the charge only on the diode on which the light falls. The physical width and height of each element is virtually equal to the element spacing and this would give rise to an aperture loss of 4 dB at the maximum attainable spatial frequency. Since the effective diode area is larger, the horizontal and vertical resolution will suffer a loss greater than 4 dB at the maximum spatial frequency and the vertical resolution will be further reduced by the effect of integration blurr.

The obvious answer to aperture loss is to use electronic aperture correction. Vertical aperture correction was used with considerable success. Horizontal aperture correction could not be used, however, because it enhanced the striations caused by element to element dark current and sensitivity variations. It was found, subjectively, that the absence of horizontal aperture correction could be offset by using rather more vertical aperture correction than normal.

7.3.5. Electronic frequency response

The frequency response of the electronic processing amplifiers and the 4.5 MHz filter was measured and confirmed to be flat to 4.5 MHz. A method has not yet been devised for checking the signal transfer from the array into the transresistance amplifier. Any shortcomings here would affect only the horizontal resolution and since, without any aperture correction, the horizontal and vertical resolutions are subjectively equal there does not seem to be any problem.

7.4. Test pictures

Figs. 17, 18, 19 and 20 show pictures taken from a picture monitor of an 8 mm film which was being scanned by the solid state sensor arrangement described in this report. Each photograph is of one television picture which was produced by scanning two consecutive frames of film at the experimental speed of 50 frames per second, as described in Section 4.3. Some vertical aperture correction has been used. Gamma correction was not used.

For the purpose of comparison each photograph of a scanned picture is accompanied by a direct enlargement of one of the two frames used to produce the scanned picture.

Both the direct and scanned pictures are of relatively poor quality because of the small format of the 8 mm film used. The most obvious defects in the scanned pictures relative to the direct pictures are the vertical striations caused by the differences in sensitivity and dark current of the individual elements in the array. If gamma correction is used these stripes become even more obvious. A broad-

cast system using this array would only be contemplated on the basis that stored correction systems would be used to remove the stripes.

The resolution of the scanned pictures is less than that of the direct enlargement. This is to be expected in view of the large number of extra processes involved in reproducing the scanned picture. The majority of the loss is probably due to the poor quality of the imaging lens and the inability to apply horizontal aperture correction without enhancing the stripes. If the stripes were removed this second problem would cease.

There is a certain amount of double exposure effect in the scanned pictures because each is composed of two frames of film. To avoid this effect, the pictures shown have been selected from parts of the film where the scene movement is a minimum. The most obvious evidence of the double exposure is that the dirt spots, each of which is relevant to only one frame of film, appear only on alternate lines of the scanned picture.

8. Conclusions and recommendations

A solid state array of photo sensitive elements has been successfully used to produce television pictures from film. These pictures have been recorded on videotape and still pictures of some frames have been obtained by photographing a picture monitor.

Sufficient data on the performance has been collected to allow assessment of the possibilities for future develop-

ments. The long term aim is to gain experience in readiness for the time when solid state area arrays suitable for television cameras become available. It has, however, become apparent during the work leading up to this report that a broadcast quality colour film scanning system could be developed using currently available devices and techniques.

The next stage of development should be to provide a stored correction system to remove the vertical striations which are caused by gain and black level variations along the array. Although this is feasible for a single dimension array it would not be practicable to store corrections for every element in an area array such as would be required in a television camera. Before area arrays become a practical proposition it will therefore be necessary to develop a technology which can produce a device without these variations. This could take several years. In the meantime, considerable benefit could be obtained by developing the use of currently available single dimension arrays for the purpose of scanning film.

9. References

1. Solid state converter for TV films. *Electronics*, 1973, **46**, 15, pp. 4E, 6E.
2. British Standard 2962 : 1958. Picture Areas of Motion Picture Films for Television.
3. CHAMBERS, J.P. 1972. Improvements in data rearrangement. British patent specification No. 57035/72.



Fig. 17 - Test pictures obtained using 8 mm film

(a) scanned picture reproduced by television monitor

(b) direct enlargement of one of the two film frames from which the scanned picture is composed



Fig. 18 - Test pictures obtained using 8 mm film

(a) scanned picture reproduced by television monitor

(b) direct enlargement of one of the two film frames from which the scanned picture is composed



Fig. 19 - Test pictures obtained using 8 mm film

(a) scanned picture reproduced by television monitor

(b) direct enlargement of one of the two film frames from which the scanned picture is composed



Fig. 20 - Test pictures obtained using 8 mm film

(a) scanned picture reproduced by television monitor

(b) direct enlargement of one of the two film frames from which the scanned picture is composed

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